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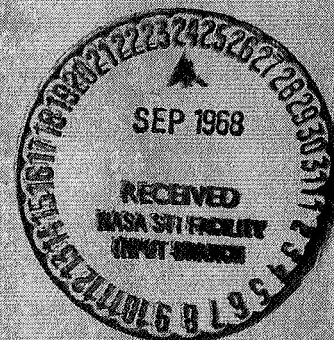
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September, 1968

PRELIMINARY REPORT

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## Gamma Ray Production in Paraffin by Cosmic Rays

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We report here the results of gamma ray production in shielding being considered for use with detectors in balloon solar gamma ray astronomy for the nuclear transition energy region. The development of directional X-ray detectors using collimation techniques has proved very successful in obtaining good angular resolution for X-rays in the 10-100 KeV range but use of the same techniques in the energy region 0.2 to 10 MeV does not achieve the same results easily. Any use of a large mass around the main central detector invariably brings in the problem of secondary radiation produced as a result of bombardment of the surrounding mass by the primary and secondary components of cosmic radiation which are present at balloon altitudes. The specific problem of interest here concerns the search for the nuclear gamma rays from the sun [Peterson, et al., 1966] [Chupp, et al., 1968] or other celestial sources.

Matteson and Peterson (1968) have investigated the effects of shielding with intermediate Z materials by surrounding a gamma ray detector with  $\approx$  12 cm of iron. Their results indicate that from 0.3 to 4 MeV the  $\gamma$ -ray counting rate with iron is higher than in free air thus indicating the importance of local production in such shielding material. Another method of background reduction involves the use of large scintillators for "active" shielding. This has been accomplished with inorganic scintillators (CsI) on several balloon flights

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(see for example [Frost, et al. (1966)] with satisfactory results in the energy range below 1 MeV. At higher gamma ray energies, however, the shields must be very large and inorganic shields of sufficient size become prohibitively expensive. There are also other problems encountered with large CsI or NaI scintillators because of their fragility and temperature dependence and long decay times. These considerations have prompted us to consider the use of organic scintillators for gamma ray shielding. The attenuation mean free path, expressed in  $\text{g/cm}^2$ , for organic scintillators is nearly the same as that in the inorganic scintillators in the 1 to 10 MeV region. Organic scintillators are also rugged, and relatively inexpensive compared to CsI or NaI. Use of the plastic scintillator is particularly bothersome, however, because the presence of hydrogen constitutes a source of the 2.22 MeV neutron-proton capture gamma rays. The flux of neutrons in the atmosphere is adequately known [Lingenfelter, 1963, Newkirk, 1963] so that an estimate could be made of the neutron capture rate in the scintillator and thereby obtain the 2.22 MeV source strength; however, the effects of local neutron production and moderation of the ambient and local neutrons before capture make the calculations difficult for practical geometries. Therefore, it was felt necessary to measure the neutron capture rate in hydrogen directly in a geometry simulating a practical shield. We could also obtain the effect of the paraffin on the continuum gamma ray spectrum in the energy range of interest as well as other background lines.

We measured the gamma ray production at balloon altitudes in large paraffin blocks which surrounded a central gamma ray detector by comparing the spectrums obtained before and after the paraffin was removed from proximity to the gamma ray detector. The schematic of the detector design is shown in Figure 1. Four boxes of household paraffin

totaling 88 lbs. were arranged in such a way that they could be removed from proximity to the central detector by use of a radio command. The detector together with the paraffin blocks was launched from Palestine, Texas on April 25, 1968 and about half an hour after the balloon reached the ceiling altitude of about  $4.0 \text{ g/cm}^2$ , the paraffin blocks were removed well away from the gamma ray spectrometer. The gamma ray spectrometer was alternately operated in two energy bands and could, therefore, measure the gamma ray spectrum in the energy region, 0.2 to 4.0 MeV with a resolution of 8% at .662 MeV. The mean geomagnetic cutoff ( $P_c$ ) during the period of interest here was 4.1 Bv. The details of the gamma ray spectrometer will be discussed in a separate paper.

The major result of the experiment is indicated in Figure 2 which shows the  $\gamma$ -ray pulse height spectrum obtained in the atmosphere with and without the paraffin in the higher energy region 1.5 to 4.0 MeV. The important new feature of the spectrum when the paraffin is around the central detector is the appearance of a 2.22 MeV gamma ray line. To emphasize the evidence for the 2.22 MeV  $\gamma$ -ray line, we have shown the pulse height spectrum at an altitude (averaged from 60 mb to 4 mb) where the effect is higher than at ceiling altitude. Also shown is a line from a  $\text{Y}^{88}$  calibration source at 1.84 MeV which was always present. In Table I, we have summarized the various counting rates in the presence and absence of the paraffin at  $4 \text{ g/cm}^2$ . Addition of the paraffin as a passive shield generally introduces two factors which affect the spectrum. Acting as an absorber for the ambient gamma ray spectrum, causes a counting rate reduction in the different energy channels while local gamma ray production in the paraffin enhances the counting rates. Column 4 in the table shows the difference in the rates with and without

paraffin. Several channels show statistically a significant increase and only the integral rate above 4.5 MeV shows a decrease. The excess counting rate in the channels (2.14 → 2.30 MeV) where the 2.22 MeV line appears is  $0.07 \pm 0.02$  counts/sec.

To determine the 2.22 MeV photopeak counting rate due to the paraffin we have used the following simple curve fitting method. The background counting rate under the photopeak is taken to be an exponentially falling spectrum over a small energy range and hence on a semilog plot a least square line could be fitted to the observed counting rates on either side of the photopeak. By subtracting an interpolated contribution from the observed counting rates in the energy region 2.14 → 2.30 MeV, the photopeak contribution is determined to be  $0.11 \pm 0.03$  cts/sec with paraffin and  $0.04 \pm 0.01$  counts/sec without paraffin. The difference, corresponding to a 2.22 MeV photon contribution from paraffin of  $0.07 \pm 0.03$  cts/sec, agrees with that obtained by direct subtracting indicating no net change in the background in this region of the spectrum when the paraffin is present.

The observations allow us to calculate the production rate of 2.22 MeV gamma rays in the paraffin. If we assume the capture rate of neutrons in the paraffin is uniform then the counting rate of the detector for the gamma ray in question is

$$R = \frac{SPd}{\mu} \cdot K \quad (\text{sec}^{-1})$$

where  $S$  = gamma ray sensitivity of detector for 2.22 MeV (efficiency x projected area) =  $1.45 \text{ cm}^2$

$P$  = production rate of 2.22 MeV photons or the source strength of these photons in the paraffin (photons  $\text{g}^{-1} \text{ sec}^{-1}$ )

$d$  = density of paraffin =  $0.98 \text{ g/cm}^3$



$\mu$  = total linear absorption coefficient of 2.22 MeV photons  
in paraffin =  $0.05 \text{ cm}^{-1}$

K = dimensionless integral over the actual distribution of the  
paraffin which includes the absorption effect. = 0.37

The value of  $S = 1.45 \text{ cm}^2$  used was extrapolated from detailed  
measurements at 0.51 MeV for the geometry of this experiment. From  
this expression and the value for K obtained by numerical integration  
we find for the experimentally determined production rate a value

$$P(\text{exp.}) = 7 \times 10^{-3} \text{ (2.22 MeV photons } \text{g}^{-1} \text{ sec}^{-1})$$

This is the average production rate in paraffin of this gamma ray line  
by all cosmic ray sources at the balloon altitude.

The only reasonable source for this line is neutron-proton  
capture since no neutron capture gamma rays are known at this energy  
for carbon. The neutrons producing the line are from two sources;  
the ambient neutrons produced in the atmosphere by cosmic rays and  
those produced locally in the paraffin. Production effects in the  
other material around the detector need not be considered since we have  
measured only the effect of the paraffin by physically removing it,  
although the data in Table I indicates this line is also evident  
without the paraffin as expected since there is still about  $2 \text{ g/cm}^2$   
of organic material surrounding the gamma ray crystal.

The calculation of the capture rate of the ambient atmospheric  
neutrons in the hydrogen of the paraffin blocks is difficult because  
the neutron density throughout the large blocks is certainly not uniform.  
However, an estimate may easily be made of the capture rate of locally  
produced neutrons assuming the production rate of the neutrons is uni-  
form. This is reasonable since the nuclear interaction mean free path  
of cosmic rays in paraffin is  $\sim 80 \text{ g/cm}^2$  compared to the block thick-

ness of  $15 \text{ g/cm}^2$ . Neglecting edge effects, then an upper limit to the neutron capture rate may be calculated from the slowing down spectrum  $\phi(E) = Q/\Sigma_s \frac{\text{neutrons}}{\text{cm}^2 \text{ sec MeV}}$  for a point source of neutrons at some energy  $E_0$  where:

$Q$  = number of source neutrons entering the system with the mean energy of the evaporation spectrum ( $\text{Neutrons cm}^{-3} \text{ sec}^{-1}$ )

$E$  = energy of slowed neutrons (MeV)

$\Sigma_s$  = energy dependent microscopic scattering cross section ( $\text{cm}^{-1}$ )

The above spectrum shape was first derived by Amaldi and Fermi (1936) for slowing down without capture; however, since the capture cross section is relatively small in hydrogen the spectrum shape should still be essentially given by the above formula. We consider then that the paraffin blocks are filled with a uniform distribution of evaporation sources  $Q$  throughout the full volume. Then neglecting edge effects an upper limit to the neutron capture rate  $P$  (theory) is calculated from

$$P(\text{theory}) = \frac{QK'}{\rho\sigma_s} \int_{E_{th}}^{E_0} E^{-3/2} dE$$

where:

$K'$ , obtained from the  $1/v$  capture cross section in hydrogen, is  $4.8 \times 10^{-29} \text{ (cm}^2 \text{ MeV}^{1/2}\text{)}$

$\rho$  = is the density of paraffin ( $0.98 \text{ g cm}^{-3}$ ) and

$\sigma_s$  = the elastic scattering cross section in hydrogen which is effectively constant over the full energy range, is taken as  $20 \times 10^{-24} \text{ cm}^2$ .

The integration limits are  $E_{th} = 2.5 \times 10^{-8} \text{ MeV}$  and  $E_0 \approx 1 \text{ MeV}$ . Using for  $Q$ , which was defined previously, a value of  $9 \times 10^{-3} \text{ neutrons gm}^{-1} \text{ sec}^{-1}$  [Boella et al., 1967] we find for  $P(\text{theory})$ ,  $2.7 \times 10^{-4} \text{ neutron captures per gram per sec (or } 2.22 \text{ MeV gammas produced per gram per sec)}$ .



Comparing with the measured neutron capture rate in paraffin of  $7 \times 10^{-3}$  neutrons per sec we find the  $\gamma$ -ray line counting rate contribution from local neutron production to be about 4%. The major contribution to the 2.22 MeV flux is therefore from the slowing down and capture of the ambient neutrons. An exact verification of this conclusion would require a detailed calculation of slowing down & capture of atmospheric neutrons in our complex geometry. Crude calculations though indicate the result is reasonable.

This result is qualitatively consistent with results of neutron production in polyethylene in rocket flights at a similar geomagnetic cutoff by Lockwood [1968]. In these experiments direct measurements of local neutron production gave a 17% contribution from locally produced neutrons as compared to albedo neutrons in a polyethylene moderated  $\text{He}^3$  neutron detector. Since at the rocket altitude the ambient neutron intensity is smaller the larger relative production effect is expected.

The increased counting rate in the energy bin  $3.0 \rightarrow 4.0$  MeV suggests the presence of other gamma ray lines introduced from the paraffin. The possibilities for lines in this energy region could be from neutron capture in carbon giving capture gamma rays at 4.96 MeV and 3.68 MeV and from inelastic scattering of protons on carbon giving the 4.44 MeV gamma ray. A combination of first and second escape of 0.51 MeV gamma rays could result in the enhancement of counting rates in the above mentioned energy region due to the various  $\gamma$ -ray lines produced in the carbon. The capture cross section of carbon ( $\sim 0.003$  barns) however seems too small to account for the large rate seen compared with the effect from hydrogen where the capture cross section is 0.3 barns.

The spectrum enhancement observed without paraffin in the energy

region 3.0 + 3.5 MeV could be due to unresolved captured gamma rays from nitrogen several of which (with one and two photon escape peaks) could account for the enhancement.

Concerning the problem of shielding from these effects in a gamma ray spectrometer surrounded by a plastic scintillator there are several factors to consider. In principle any fast ( $> 100$  KeV) neutrons from the atmosphere or those locally produced can be gated off by anti-coincidence circuitry as they produce recoils in the plastic scintillator. Also the interaction of primary or secondary cosmic rays which produce neutrons (whether they be from charged or neutron particles) will likely produce an ionizing nuclear "star" and be gated off. The hydrogen capture gamma ray may be eliminated by use of a deuterated organic scintillator.

In conclusion it is interesting to note that surrounding the detector with paraffin does not significantly enhance the spectrum except at 2.22 MeV. This is undoubtedly the consequence of the fact that the production rate of gamma rays per gram by cosmic rays and the absorption coefficients in air and paraffin are essentially similar.

In the line of investigations to study other aspects of the shielding problem for gamma ray telescopes we plan to utilize a large plastic scintillator surrounding a gamma ray spectrometer, and operated both in coincidence and anti-coincidence to further investigate this aspect of the shielding problem.

## ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

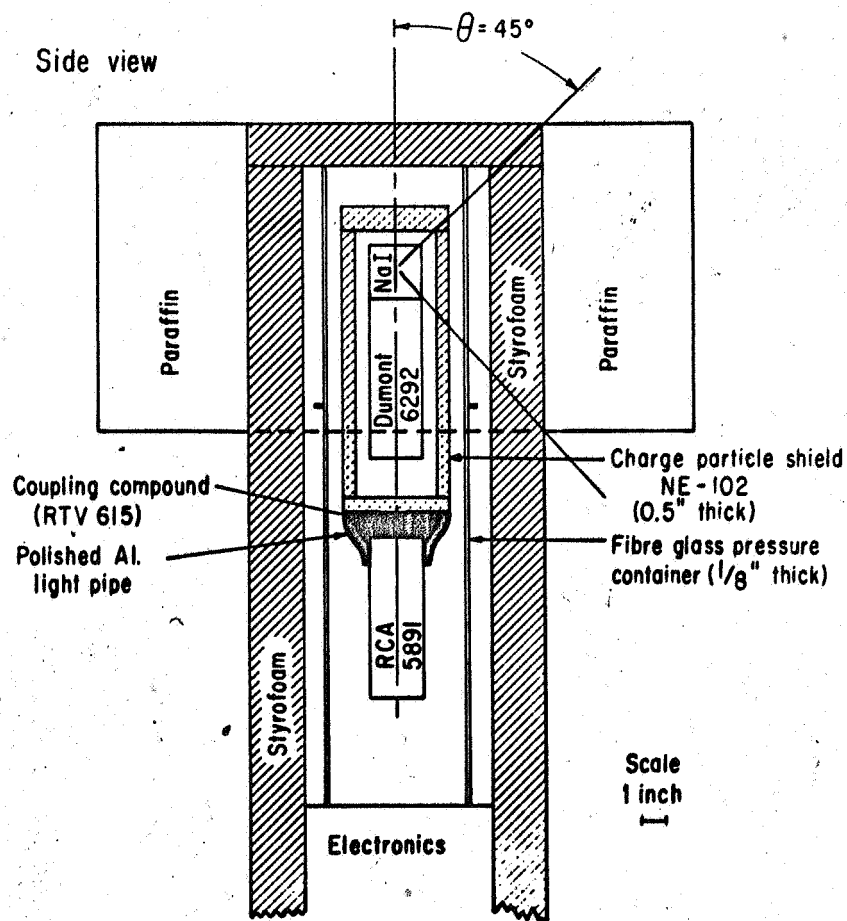
Figure 1      A schematic diagram showing the  $\gamma$ -ray spectrometer surrounded by paraffin blocks which were lowered during the later part of the balloon flight at altitude.

Figure 2      The pulse height spectrum obtained at high altitudes using a  $\gamma$ -ray spectrometer with and without the presence of paraffin blocks nearby.

PARAFFIN BLOCK EXPT.

Energy Region MeV	Counts/sec		
	With Paraffin	Without Paraffin	Difference (with-without)
0.3 - 0.4	10.96 $\pm$ 0.14	9.79 $\pm$ 0.06	+ 1.17 $\pm$ 0.15
0.4 - 0.6	10.83 $\pm$ 0.13	11.13 $\pm$ 0.07	- 0.30 $\pm$ 0.15
0.6 - 0.7	2.96 $\pm$ 0.07	3.11 $\pm$ 0.04	- 0.15 $\pm$ 0.08
0.7 - .08	2.74 $\pm$ 0.07	2.34 $\pm$ 0.03	+ 0.40 $\pm$ 0.08
> 0.8	23.89 $\pm$ 0.20	23.95 $\pm$ 0.01	- 0.06 $\pm$ 0.20
0.51 MeV Area	1.05 $\pm$ 0.14	1.01 $\pm$ 0.08	+ 0.04 $\pm$ 0.16
2.0 - 2.5	1.15 $\pm$ 0.03	1.02 $\pm$ 0.02	+ 0.13 $\pm$ 0.04
2.5 - 3.0	0.74 $\pm$ 0.025	0.77 $\pm$ 0.01	- 0.03 $\pm$ 0.03
3.0 - 3.5	0.74 $\pm$ 0.025	0.66 $\pm$ 0.01	+ 0.08 $\pm$ 0.03
3.5 - 4.0	0.52 $\pm$ 0.02	0.50 $\pm$ 0.01	+ 0.02 $\pm$ 0.02
4.0 - 4.5	0.50 $\pm$ 0.02	0.50 $\pm$ 0.01	0.00 $\pm$ 0.02
> 4.5	4.24 $\pm$ 0.06	4.58 $\pm$ 0.05	- 0.34 $\pm$ 0.08
2.22 $\pm$ 0.08	0.41 $\pm$ 0.02	0.340 $\pm$ 0.006	+ 0.07 $\pm$ 0.02
2.2 MeV Peak Area by Curve Fitting	0.110 $\pm$ 0.03	0.042 $\pm$ 0.012	+ 0.07 $\pm$ 0.03

TABLE I



Top view

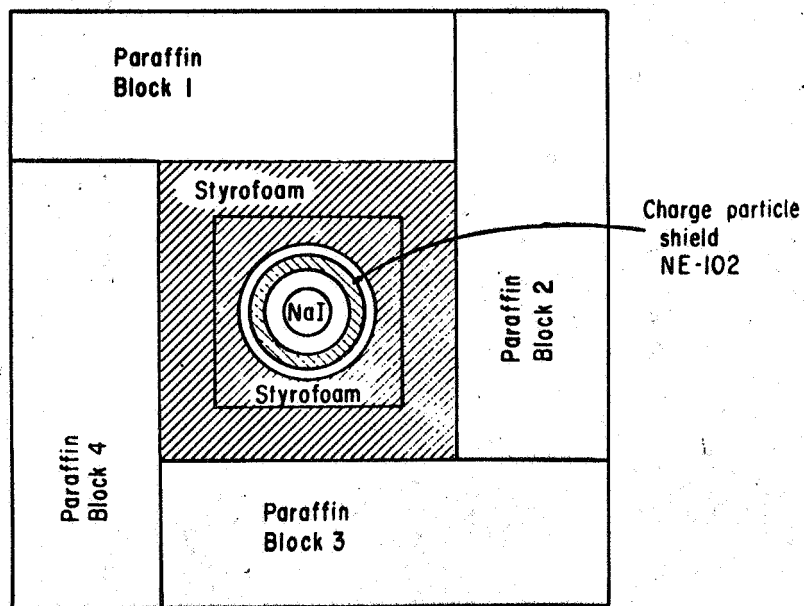


FIGURE 1



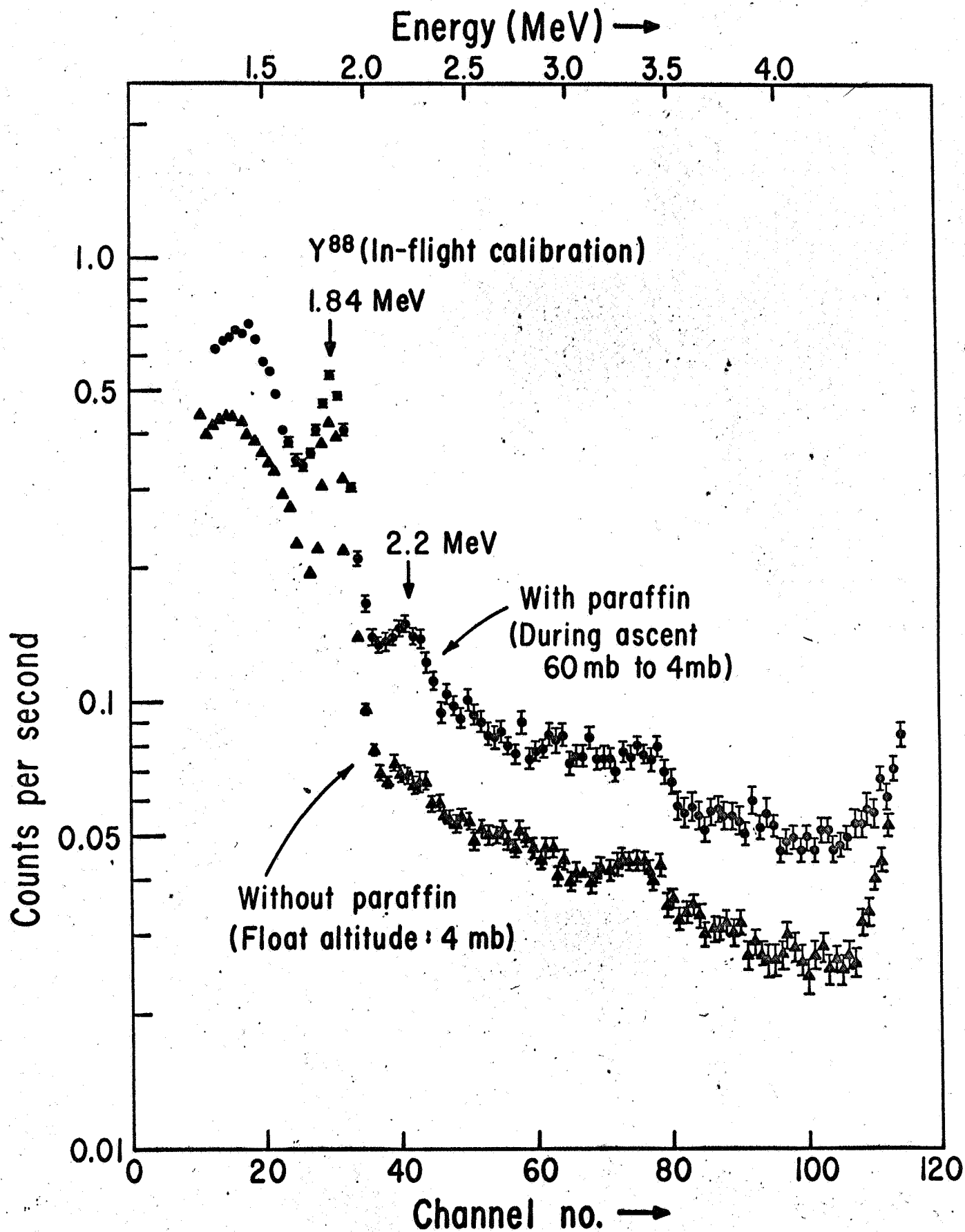


FIGURE 2